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Surface-Soil Properties and Water Contents across Two Watersheds with Contrasting Tillage Histories

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ABSTRACT

Soil properties and water contents (θ) vary spatially, but management effects on spatial patterns are poorly understood. This study's objective was to compare surface-soil properties and θ in two small watersheds (30–43 ha) in Iowa's loess hills. Both watersheds were in continuous corn (*Zea mays* L.) from 1972 through 1995, one (CW1) under conventional tillage and the other (RW3) under ridge tillage. In 1996, CW1 was converted to no-till. Surface-soil (0–0.2 m) samples were collected along hillslope transects during 2002 and 2003, including four dates with water-content measurements by gravimetry in both watersheds. Soil bulk density (ρ_b), organic carbon (OC), and texture were determined, along with terrain attributes (elevation, slope, surface curvature, contributing area, and wetness index). After accounting for landscape-position effects, RW3 had more OC (2.1 versus 1.7%) and smaller ρ_b (1.16 versus 1.25 Mg m^{-3}) than CW1 ($P < 0.001$). Larger θ values occurred in RW3 ($P < 0.002$) when θ was >33%. Landscape position and terrain attributes better explained variation in θ in RW3 than CW1. Also, OC was correlated with θ in RW3, but not in CW1. Soil textures were similar (within 2%,) but finer in CW1 ($P < 0.05$). Pedotransfer functions confirmed that differences in soil properties between watersheds resulted in greater θ in RW3 than CW1, particularly at low soil-water potential, and that more distinct patterns of θ should occur in RW3. Results indicate long-term conventional tillage in CW1 affected soil properties and water-holding characteristics in ways that decreased water retention and muted spatial patterns of θ.

Variation in soils across landscapes influences crop productivity and watershed hydrology. Coupled with landscape effects on soils, agricultural management systems also affect soil properties, including organic matter content (Cambardella et al., 2004; Rhoton, 2000), aggregation (Cambardella and Elliott, 1993), and ρ_b (Logsdon et al., 1999b). Management systems can affect θ (Johnson et al., 1984) and the efficiency of soil-water uptake by plants (Hatfield et al., 2001; Varvel, 1994). Management also affects off-site impacts of agriculture by influencing infiltration, runoff, and erosion (Rhoton et al., 2002). Yet, our understanding of management impacts includes little about their effects on spatial variations in soil properties and θ across landscapes.

Variation in soil properties has been evaluated in relation to landscape position (Ruhe and Walker, 1968), and terrain characteristics obtained from digital elevation data (Moore et al., 1991). A number of soil properties can differ according to landscape position, including horizon thickness, texture, organic matter, aggregate stability, carbonates, Mn, redoximorphic features, pH, and exchangeable cations (Brubaker et al., 1993; Cambardella et al., 2004; Cassel et al., 2002; Pierson and Mulla, 1990; Young and Hammer, 2000). Impacts of erosion on soil properties at different landscape positions have also been examined (Kreznor et al., 1989). Terrain characteristics including slope, aspect, contributing area, profile curvature, wetness, and stream-power indices (Moore et al., 1991) can be used to predict and map soil attributes such as A-horizon thickness and color, profile thickness, organic matter content, pH, and texture (Gessler et al., 2000; Moore et al., 1993; Thompson et al., 1997). Park and Burt (2002) showed the predictive capacity of terrain features depends on depth and the soil property of interest. At broad spatial scales, Bell et al. (1994) showed terrain attributes can predict soil drainage class across large areas.

The spatial distribution of θ has also been studied in relation to landscape position and terrain characteristics. Increases in plant-available soil water in toeslope and/or footslope positions have been attributed to infiltration of runoff that originates upslope and/or shallow water tables (Afyuni et al., 1993; McGee et al., 1997). Topographic attributes reflecting lateral flows and accumulations at the landscape scale have been statistically related to θ (Tomer and Anderson, 1995; Western et al., 1999) and water retention characteristics (Pachepsky et al., 2001). The prediction of hydraulic parameters using pedotransfer functions (Wösten et al., 2001) can be improved if terrain attributes (e.g., slope, aspect) are included among the independent variables (Romano and Palladino, 2002).

The capacity of terrain attributes to account for spatial patterns of θ may depend on the temporal stability of these patterns. Temporal stability in θ patterns can be associated with the arrangement soil types and textures on the landscape (da Silva et al., 2001). In other instances, temporal stability has been found in sandy and/or flat terrain, (Tomer and Anderson, 1995; Wendroth et al., 1999) where runoff and shallow lateral flows are rare. However, on landscapes where runoff and/or lateral movement of shallow soil water do occur, temporal instability in patterns of soil moisture has been reported (Grayson et al., 1997). This instability occurs because topographically driven lateral flows dominate spatial patterns when there is surplus moisture (precipitation > evapotranspiration), but spatially random variation prevails when dry conditions restrict lateral water movement. Accordingly, Western et al. (1999) found the proportion of variation in θ accounted by terrain indices varied from 22 to 61%,

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Abbreviations: A_{sc}, specific contributing area (m m^{-2}); C_s, surface curvature (m m^{-1}); CW1, conventionally tilled watershed; OC, organic carbon (%); RW3, ridge-tilled watershed; Z, relative elevation (m); ω, topographic wetness index.

depending on average θ. Temporal stability (or instability) results from several scale-dependent factors that determine θ (Kachanoski and de Jong, 1988), including landform, soil-type variation, and agricultural practices.

Among these studies of landscape patterns of soils and soil hydrology, we found none that evaluated management effects on spatial patterns of soil properties and θ by comparing paired landscapes. This study examined this issue, using two similar watersheds where effects of management on hydrology and soils have been documented. Between 1971 and 1995, both watersheds were cropped to continuous corn but differed in tillage management, with one watershed under conventional chisel plow and disk tillage and the other under ridge tillage (Karlen et al., 1999). Average annual sediment discharged from the watersheds was significantly greater from the conventionally managed watershed than the ridge till–managed watershed (Kramer et al., 1999; Moorman et al., 2004). There was less surface runoff under ridge tillage compared to conventional tillage, but an increase in baseflow (Kramer et al., 1999; Tomer et al., 2005). Logsdon et al. (1999a) evaluated annual water budgets and corn grain yield, and found greater water use efficiency under ridge till compared to conventional till. The difference was attributed to greater residue cover under ridge till and its effect in reducing soil-water evaporation. Surface-soil (0–0.15 m) OC content and aggregate stability were smaller and ρ_b was greater in the conventionally managed watershed relative to the ridge-tilled watershed in 1995, at the end of the 25-yr experiment (Cambardella et al., 2004; Moorman et al., 2004).

This study compared the spatial variability of surface-soil properties (ρ_b, OC, and texture) and water contents (θ) between the conventionally tilled and ridge-tilled watersheds, 8 yr after the conventionally tilled watershed was converted to no-till. The contrast in management histories had documented impacts on soil properties and watershed hydrology (Karlen et al., 1999; Kramer et al., 1999; Logsdon et al., 1999a; Cambardella et al., 2004; Moorman et al., 2004). This study was aimed to extend results of these studies by addressing four objectives:

1. To compare soil properties (ρ_b, OC, and texture) and their spatial patterns in the surface soils of these two watersheds (and implicitly, to determine if differences in ρ_b and OC identified in 1995 were still detectable in 2003);
2. To identify any differences in θ and spatial patterns of θ between the two watersheds;
3. To evaluate the effects of soil properties on θ and its spatial distribution in both watersheds;
4. To evaluate the temporal stability of spatial patterns of θ in both watersheds.

MATERIALS AND METHODS

Setting

The study setting was western Iowa's Loess Hills (Prior, 1991), at the Deep Loess Research Station (Karlen et al., 1999). This study took place in Watersheds 1 (CW1, 30 ha) and 3 (RW3, 43 ha), which are separated by a distance of 4 km. Soils were developed in deep (10–25 m) uniform loess and loess-derived alluvium (Karlen et al., 1999). Based on a first-order soil survey (Charles Fisher, unpublished data, 1970), soils are similarly distributed in the two watersheds, with 62 to 66% covered by Typic Hapludolls (Monona series [fine-silty, mixed, superactive, mesic Typic Hapludolls]), 10 to 16% by Typic Udorthents (Ida and Dow series [fine-silty, mixed, superactive,calcareous, mesic Typic Udorthents]), and 22 to 24% by Cumulic Hapludolls (Napier and Kennebec series [fine-silty, mixed, superactive, mesic Cumulic Hapludolls]) (Soil Survey Staff, 2003).

The two watersheds were managed with contrasting conservation practices since 1963 (Karlen et al., 1999). CW1 was in continuous corn and conventional (moldboard or chisel and disk) tillage between 1963 and 1995. RW3 was in pasture from 1963 until 1971, then converted to continuous corn production with a conservation tillage system known as ridge till (Klein et al., 1996). Management of the watersheds was changed after 1995. CW1 was converted to a corn and soybean [*Glycine max* (L.) Merr.] rotation with a no-till system in 1996. RW3 was kept in ridge till and continuous corn through 2000, and then converted to a corn and soybean rotation with minimal tillage. After leveling of the ridges in 2001, a seedbed preparation by disking in 2002 (before this study) was the only subsequent tillage in RW3.

Sampling and Measurements

Daily precipitation recorded for each watershed by averaging data from two tipping-bucket rain gauges per watershed, except during winter (December through March) when only one gauge per watershed was maintained. Soil-sampling transects were established along slope lengths to include ridge–interfluve, shoulder, backslope, footslope, and toeslope positions (Ruhe and Walker, 1968), as interpreted in the field. (Ridge–interfluve is hence referred to as "ridge." The upper positions included few interfluve locations due to their limited extent in this dissected terrain.) Transects were placed along slopes with linear, convex, and concave contours. There were 50 sampling locations in CW1 and 62 locations in RW3 (Fig. 1). Although fewer samples were collected in CW1, there was a greater density of sampling locations in CW1 due to its smaller size. Sampling locations were GPS-surveyed using a Trimble Pathfinder XRS receiver (1 m accuracy; Trimble Navigation Ltd., Sunnyvale, CA). Only cropped areas were sampled; waterways, buffers, and areas with different ownership or management were excluded (Fig. 1).

Soil-moisture samples were collected by hand on nine dates in CW1 and on eight dates in RW3 between June 2002 and November 2003. Samples were collected within a 2 by 2 m area at each location, which was marked with a flag. One person collected all samples to help ensure sampling consistency. This influenced sampling logistics, and sampling did not occur when wet conditions limited vehicle or foot access, or when dry conditions slowed hand-probe sampling (due to penetration resistance) and prevented sampling of all locations in a single day.

Individual soil samples were bulked from triplicate cores (taken from crop-row, nontrafficked interrow, and halfway between row and interrow positions) with a 38-mm-diameter hand probe to a 200-mm depth. To allow an assessment of local sampling error, duplicate samples were taken in each watershed during May 2003 (15 May in CW1, 21 May in RW3). A further assessment of sampling error was done with the final sampling in November 2003, when in addition to the hand-probe cores, cores were also collected with a thin-sleeve, hammer-driven bulk density sampler, with triplicate cores bulked at each of the three row positions (three bulked samples per location). This

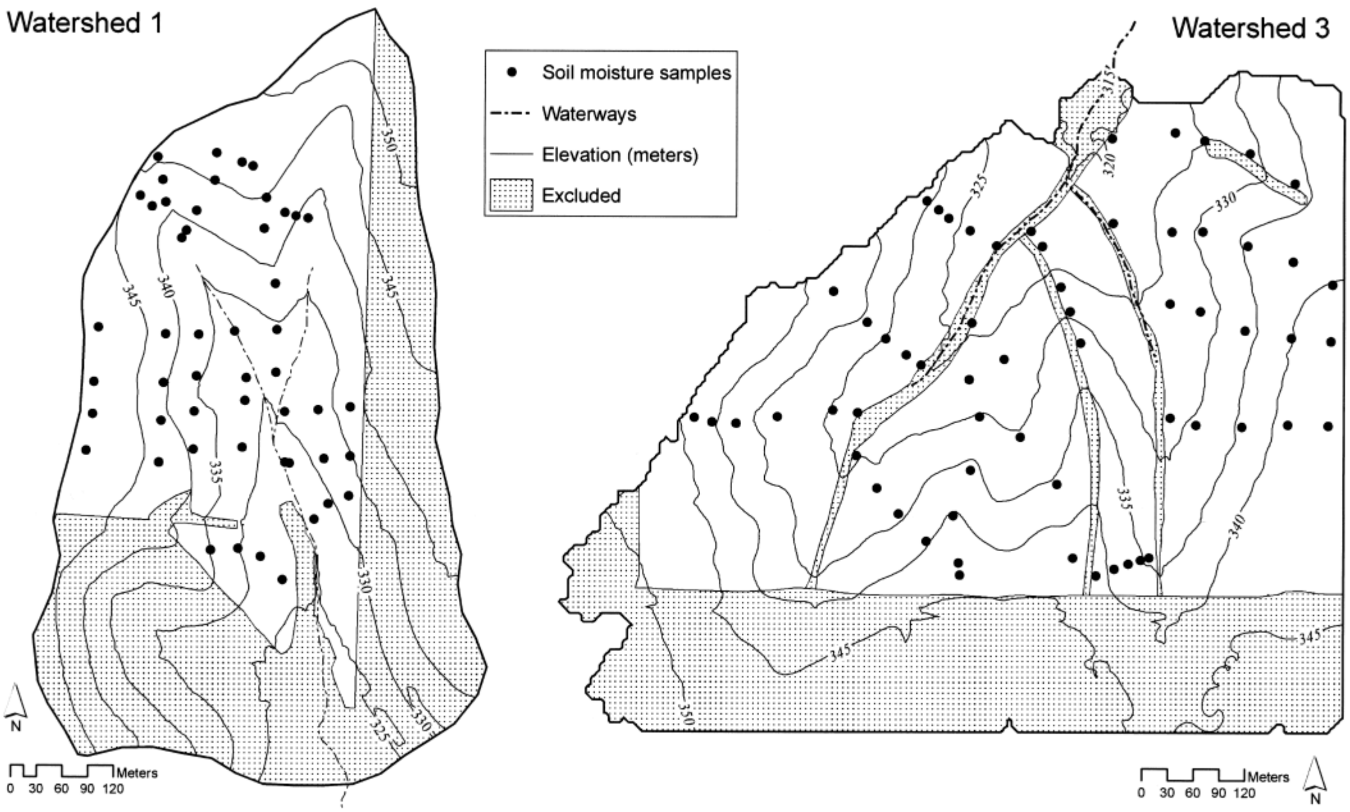

Fig. 1. Map of watersheds 1 and 3 (CW1 and RW3), showing sampling locations. Excluded areas include roadways, buffers, waterways, and areas in different ownership or management.

provided a check on ρ_b values determined using the hand-probe cores, and for one sampling date, provided samples from each row position at all locations. Samples were sealed in plastic bags and stored in a cooler for transport to the laboratory where water contents were determined gravimetrically by oven drying at 105°C for 24 h. Bulk density was calculated by dividing the sample dry mass by its volume.

Our analysis of θ is based on data from four dates of sampling from both watersheds: 21 June and 1 Nov. 2002, and 28 Mar. and 15 May 2003 (we used the first replicate from CW1 on 15 May 2003). However, analysis of ρ_b included data from all dates (550 samples collected in CW1 and 620 samples collected RW3, including replicate and sleeve-core data). The cores collected with the thin-sleeve sampler had similar ρ_b values to those collected using the hand probe (based on a single-factor ANOVA, $P > 0.05$). To convert gravimetric θ to volumetric, the average ρ_b value across all sampling dates was used at each location to minimize effects of ρ_b sampling errors (which considerably exceeded θ sampling errors).

The final hand-probe samples (collected November 2003) were subject to total C analyses using a dry combustion method (Nelson and Sommers, 1986). Inorganic C was determined by a modified pressure calcimeter method (Scherrod et al., 2002) and results subtracted from total C to obtain OC. The samples were also subjected to textural analysis by the hydrometer method (Gee and Bauder, 1986).

Terrain Attributes

Terrain attributes were calculated from digital elevation models with a 5-m grid-cell size. Moorman et al. (2004) described the construction of these models in detail. Terrain attribute values were extracted for the GPS-surveyed sampling locations to allow correlation with soil properties and θ. The attributes included relative elevation (Z), slope (S), surface curvature (C_s), specific contributing area (A_{sc}), and topographic wetness index (ω). Slope was calculated from the steepest descent to a neighboring cell, A_{sc} was calculated using the omnidirectional (or D_∞) method of Tarboton (1997), and C_s was determined by the omnidirectional method of Blaszczynski (1997). Blaszczynski's C_s parameter provides a distance-weighted average rate of elevation change between a centroid cell and its neighbors, in this case those within an 11 by 11 cell window. (Use of a smaller window was evaluated but did not give better correlations with the soil variables.) The index ω was calculated as the log of the quotient of specific contributing area divided by slope (Wilson and Gallant, 2000).

Data Analysis

First, spatial autocorrelation in soil properties and θ was assessed to determine if autoregressive statistics would be necessary. Correlograms (Robertson, 2000) were calculated with a lag interval of 50 m (the shortest mean lag was 35 m). Elevation (Z) was the only variable to show autocorrelation at $>$50 m, and only two of the terrain attributes (S, A_{sc}) showed significant spatial correlation at 35 m. However, the dependent variables (soil properties and θ), showed essentially no autocorrelation at 35 m ($r_{lag35} < 0.3$), and we proceeded with standard statistical procedures assuming spatial independence of our soil measurements.

To meet the first two objectives, two approaches were used to analyze variation in soil properties (ρ_b, OC, percentages of silt and clay) and θ (for the four dates of common sampling) within and between the two watersheds. The first approach was to compare data between watersheds, as classified according to landscape position. A factorial ANOVA was applied to test for effects of landscape position (block), watershed (treatment), with a block × treatment interaction. Note that for ρ_b, data from all sampling dates ($n = 1170$) were included. The interaction was not significant for any of the variables ($P > 0.1$). Therefore, the interaction term was dropped, and only results from ANOVA that modeled main effects are reported here. Transformations (inverse, or inverse squared) were applied as required to meet variance and normality assumptions, with normality tested by the Wilk–Shapiro method. Duncan's multiple range tests were applied to determine differences between landscape positions, among and within watersheds. Differences between watersheds at each landscape position were separately identified by a single-factor ANOVA, while differences between watersheds among landscape positions was tested using the F ratio from the type III sums of squares of the factorial ANOVA, which removed any effect of landscape position on the comparison. We regarded $P < 0.05$ as significant in all instances.

The second approach to identify and compare spatial patterns was to identify correlations and predictive relationships between terrain parameters and soil properties and θ. Correlation matrices and data plots between terrain and soil variables were constructed. Regression procedures were undertaken to determine if the terrain attribute data could predict soil properties and θ. These regressions included simple linear, multiple linear (by stepwise regression), and second-order expressions with interaction terms (using backward selection to optimize r^2). In the multiple regressions only primary terrain variables based on elevation (Z) and its local changes (S, C_s) were used, due to colinearity with secondary attributes (A_{sc}, ω). Regression results for CW1 and RW3 were compared in terms of 95% confidence intervals for coefficients, and the predictive capacity of the terrain attributes (r^2). Overall, we used two lines of evidence to infer differences in spatial patterns of soil properties and θ between watersheds: by comparing landscape-position effects between watersheds (ANOVA) and by comparing terrain-attribute correlations and regressions between watersheds.

Objective 3 was met by evaluating correlations and applying pedotransfer functions (Mayr and Jarvis, 1999). The underlying hypothesis to this objective is that any observed differences in θ between watersheds and/or landscape positions should be consistent with observed differences in soil properties. First, correlations between θ and soil properties were evaluated in each watershed, and stepwise regression analysis was applied to predict θ from the soil properties. Second, soil property data (ρ_b, OC, and texture) were entered into pedotransfer functions given by Mayr and Jarvis (1999), which use ρ_b, OC, and fractions of sand, silt, and clay to estimate the constants of a modified soil water retention curve (Brooks and Corey, 1964; Hutson and Cass, 1987):

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi}{\alpha}\right)^{-\frac{1}{b}} \qquad [1]$$

In Eq. [1], θ_s is saturated water content, θ_r is residual water content, ψ is soil water potential, and α and b are constants. The α parameter is related to the air entry potential (ψ_e) (Hutson and Cass, 1987). We used Mayr and Jarvis's (1999) equations to estimate θ_s and b for each sample location, but modified their approach to estimate global values of α and θ_r, using unpublished data θ(ψ) from these watersheds. Mayr and Jarvis (1999) recommended use of location-specific data to estimate α if possible, because their equation to estimate α had an r^2 of only 0.34. Therefore, we used a matching point based on ($\psi = -10$ KPa, $\theta = 0.37$) to estimate a single global value of 24.8 for α, using pedotransfer-based estimates of 0.54 for θ_s and 2.65 for b, obtained using average soil properties. Also, while Mayr and Jarvis (1999) assumed $\theta_r = 0$ (per Campbell, 1974), we found that a value of $\theta_r = 0.12$ provided estimates of θ at 1500 KPa within the expected range of 0.15 to 0.20. These estimates of θ_r and $\theta_{1500\ KPa}$ are consistent with limited (Rob Malone, unpublished data, 2004; Tom Steinheimer, unpublished data, 1996) θ(ψ) data from these watersheds in the dry range and published data for silty clay loam soils (Rawls et al., 1991). The estimates of b and θ_s at each sampling locations were subjected to ANOVA to identify differences between landscape positions and watersheds, as described above for soil properties and θ. Soil water retention curves based on pedotransfer function results were plotted to evaluate observed θ values and differences between watersheds.

The fourth objective was simply met using correlation matrices and plots of θ data from each watershed on different dates, to evaluate the temporal consistency of spatial patterns of θ. Statistical software included SAS/LAB, SAS/INSIGHT, and SAS/ANALYST (SAS Institute, 1999) for ANOVA and regression procedures.

RESULTS AND DISCUSSION

Similarity of Watersheds

The terrains of these two watersheds are shown similar by scatter plots between variables that determine topographic exposure (Z versus C_s, Fig. 2A) and soil wetness (A_{sc} versus S, Fig. 2B). Both plots show CW1 and RW3 overlie one other, and therefore the sampled locations in the two watersheds are similar in terrain characteristics that influence soil wetness and topographic exposure. Although CW1 is on average steeper than RW3, the difference is only 0.5% (Karlen et al., 1999), and our sampling points were similar in terms of all terrain characteristics, according to t tests ($P > 0.35$).

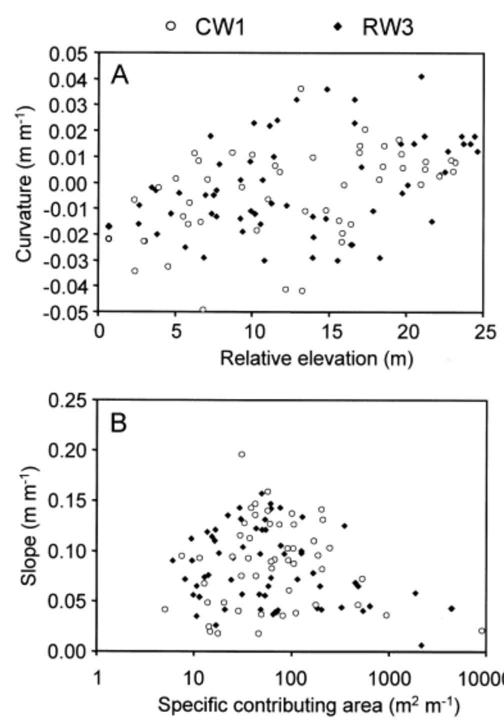

Fig. 2. Plots of terrain characteristics at sampling locations in CW1 and RW3 show the two watersheds are similar in terms of topographic exposure (A) and soil wetness (B).

Table 1. Statistical comparisons of silt and clay among and between landscape positions and watersheds.†

Parameter	Landscape position	Mean (CW1 and RW3)	CW1 mean	RW3 mean	P (CW1 = RW3)‡
		% mass			
Silt§	Ridge	57.6 a	55.1 a	58.7 a	ns
	Shoulder	56.5 ab	55.2 a	57.7 ab	ns
	Backslope	55.0 b	55.0 a	54.9 b	ns
	Footslope	56.2 ab	54.5 a	57.5 ab	0.002
	Toeslope	56.8 ab	56.1 a	57.2 ab	ns
	All	56.3	55.2	57.1	0.002
Clay¶	Ridge	38.4 b	41.0 a	37.2 b	ns
	Shoulder	39.7 ab	40.6 ab	38.9 ab	ns
	Backslope	41.0 a	40.8 a	41.1 a	ns
	Footslope	39.1 ab	40.0 ab	38.4 ab	ns
	Toeslope	38.7 ab	38.8 b	38.7 ab	ns
	All	39.5	40.2	38.9	0.04

† CW1, conventional tillage watershed; RW3, ridge tillage watershed. Comparisons between landscape positions (column-wise) are indicated by lettered significance groupings from Duncan's multiple range tests; landscape positions not sharing a letter are different at $P < 0.05$. In the last column, significance of differences between watersheds (row-wise) are based on single-factor ANOVAs at each landscape position and multiple-factor ANOVA (type III sums of squares) among landscape positions.
‡ ns, not significant ($P > 0.05$).
§ Square transformation (X^2) transformation applied to meet normality.
¶ Inverse squared transformation (X^{-2}) applied.

Across both watersheds, soil textures were silty clay loams. Parent materials are deep and uniform in this area, which is reflected in the small variation of textural data (Table 1). On average, RW3 had greater silt and lesser clay fractions than CW1, but differences were less than 2%. In RW3 there were significant differences in texture between backslope and ridge positions, but only of about 4%. Slope was correlated with silt ($r < 0$) and clay ($r > 0$) contents among watersheds and in RW3 ($P < 0.05$), but in CW1 no terrain attribute was significantly correlated with textural data (not shown). These differences, while small, could influence spatial patterns of ρ_b, OC, and/or θ. Sand contents ranged between 3 and 7% (not shown).

Rain-gauge data showed that antecedent precipitation for four dates of soil-moisture sampling was similar between watersheds except for 15 May 2003, when CW1 had recently received 13 mm more than RW3 (Table 2). Such a difference could be important, but on this date, soil profiles were well wetted by spring rains, and the additional precipitation in CW1 had opportunity to redistribute below the 0.2-m depth before sampling. This point is revisited later in the paper. Tomer et al. (2005) reported that during a 25-yr period (1971–1995), CW1 received about 2% more precipitation than RW3.

Table 2. Antecedent precipitation and crop conditions for four dates of sampling in watersheds CW1 and RW3.

Sampling date	Antecedent precipitation: Prior 5 d CW1	Prior 5 d RW3	Prior 10 d CW1	Prior 10 d RW3	Prior 30 d CW1	Prior 30 d RW3	Surface or crop condition
	mm						
21 June 2002	<1	<1	1	1	71	73	Near canopy closure
1 Nov. 2002	6	6	19	19	39	34	Postharvest
28 Mar. 2003	3	5	18	14	21	18	Winter fallow
15 May 2003	30	17	63	48	154	139	Crop emergence

Bulk Density and Organic Carbon

Bulk density showed significant differences between watersheds at all landscape positions ($P < 0.001$; Table 3), but no significant variation among landscape positions ($P > 0.05$). The magnitude of the difference in ρ_b between watersheds was similar to that found in 1995 (Cambardella et al., 2004). The difference could result from greater aggregate stability in RW3 (Cambardella et al., 2004), and/or greater exposure of subsoils in CW1 through erosion during >30 yr of conventional tillage (Kramer et al., 1999). Greater ρ_b in conventionally tilled versus no-till plots has been reported on loess soils (Rhoton et al., 2002). In this case, the greater ρ_b found in CW1 in 1995 after more than 30 yr of conventional tillage apparently persisted through 8 yr of subsequent no-till. Note that in both watersheds, ρ_b was about 10% greater than found in 1995 by Cambardella et al. (2004). A sampling-depth difference (0.2 m in 2003 versus 0.15 m in 1995) would contribute to this difference.

Across all sampling dates (n of 550 in CW1 and 620 in RW3), the standard deviation of ρ_b was about 0.1 Mg m^{-3} in both watersheds. A pooled ANOVA ascribed about a third of the total variance to sampling date and about 8% to watershed. Also, ANOVA on paired-sample data collected May 2003 showed about 30% of variation was due to short-range variation and sampling error.

Differences in OC occurred between watersheds and landscape positions (Table 3). The average OC was about 1.7% in CW1 and 2.1% in RW3, with a standard deviation of about 0.3% in both watersheds. Less OC was found in CW1 than RW3 at all landscape positions except the ridge. Less OC was found at backslope positions compared to the ridge in CW1 and the toeslopes in RW3. The difference in OC concentration between watersheds averaged about 0.4%, but was 0.6% at the toeslope positions (Table 3). The severe erosion that

Table 3. Statistical comparisons of bulk density (ρ_b) and organic C (OC) among and between landscape positions and watersheds.†

Parameter	Landscape position	Mean (CW1 and RW3)	CW1 mean	RW3 mean	P (CW1 = RW3)‡
		Mg m^{-3}			
ρ_b§	Ridge	1.19 a	1.24 a	1.17 a	<0.001
	Shoulder	1.20 a	1.24 a	1.17 a	<0.001
	Backslope	1.20 a	1.24 a	1.16 a	<0.001
	Footslope	1.20 a	1.25 a	1.16 a	<0.001
	Toeslope	1.19 a	1.24 a	1.15 a	<0.001
	All	1.20	1.24	1.16	<0.001
		% mass			
OC	Ridge	1.99 a	1.92 a	2.04 ab	ns
	Shoulder	1.86 ab	1.64 ab	2.05 ab	0.03
	Backslope	1.72 b	1.51 b	1.91 b	<0.001
	Footslope	1.94 a	1.70 ab	2.10 ab	0.01
	Toeslope	2.02 a	1.67 ab	2.30 a	<0.001
	All	1.89	1.66	2.08	<0.001

† Comparisons between landscape positions (column-wise) are indicated by lettered significance groupings from Duncan's multiple range tests; landscape positions not sharing a letter are different at $P < 0.05$. In the last column, significance of differences between watersheds (row-wise) are based on single-factor ANOVAs at each landscape position, and multiple-factor ANOVA (type III sums of squares) among landscape positions.
‡ ns, not significant ($P > 0.05$).
§ Analysis of ρ_b based on data from all sample dates with n of 550 in CW1 and 620 in RW3.

occurred in CW1 under >30 yr of conventional tillage (Kramer et al., 1999) may have eroded subsoils with little OC from the slopes and deposited this low-OC sediment at toeslopes, contributing to a larger difference at this landscape position. However, this apparent difference in pattern did not result in a significant landscape by watershed interaction in the ANOVA ($P = 0.15$). The greater OC content in RW3 contributes to greater aggregate stability (Cambardella et al., 2004) and may contribute to the differences in ρ_b. Similar associations between OC, aggregate stability, and ρ_b have been reported (Rhoton et al., 2002). We found ρ_b (averaged across dates) and OC were negatively correlated in both watersheds ($P < 0.01$), but with little predictive power (r^2 of linear regression about 0.10; not shown).

The difference in OC between watersheds was significant ($P < 0.001$) whether expressed as a concentration (mass percentage) or mass per unit area (Mg ha^{-1}). Averages from Table 3 convert to 41.3 Mg OC ha^{-1} in CW1 and 47.9 Mg OC ha^{-1} in RW3, to a 0.2-m depth. There was an apparent increase in OC concentration of about 10% in both watersheds between 1995 (Cambardella et al., 2004) and 2003, which could result from differences in sampling depth and locations. For CW1, a 10% increase in OC would be considered modest compared to other reports of OC change after conversion to no-till (Edwards et al., 1992; Reicosky et al., 1995).

Soil properties (ρ_b and OC) showed significant correlations with terrain attributes (Table 4). However, ρ_b had only one weak correlation with C_s in RW3. Because ANOVA showed no ρ_b differences among landscape positions (Table 3), spatial patterns of ρ_b were not further assessed. Several terrain parameters were correlated with OC in RW3, however, slope was the only parameter correlated with OC in both watersheds and a negative linear relationship with slope gave r^2 values of 0.21 and 0.25 (Fig. 3). The mean difference in OC between watersheds caused a significant difference in intercepts, but the two regression slopes were similar, because the coefficient's 95% confidence intervals overlapped. Moorman et al. (2004) also found slope was most consistently correlated with OC in these watersheds. They showed greater correlation between OC and slope than shown in Table 4, but accrued OC to 0.9-m depth. Although no other terrain attributes showed correlations with OC in CW1, through backward selection we identified multiple second order expressions, including S, Z, and C_s, that accounted for 52 to 55% of the variation in OC in both watersheds and were statistically similar to one another (not shown). Other studies have shown simple linear regressions with terrain parameters, particularly ω, can account for 48 to 78% of variance in organic matter (Moore et al., 1993; Gessler et al., 2000), but such studies have often been on single hillslopes. Depth of sampling and size of the sampled area will clearly influence these types of relationships.

Overall, differences in amounts of OC between the two watersheds are indicated by the intercepts of linear regressions (Fig. 3) and by ANOVA results (Table 3). Spatial patterns are also evident using both approaches, but any evidence that spatial patterns of OC are different between the two watersheds is weak, because the landscape position by watershed interaction was not significant in the ANOVA, and slope terms in linear regression expressions cannot be distinguished between watersheds.

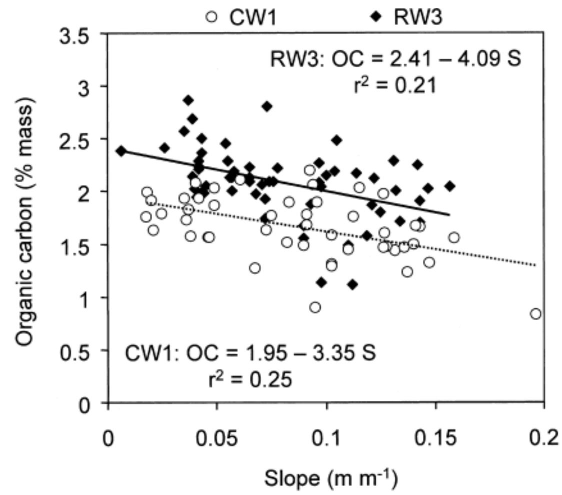

Fig. 3. Plots of slope and organic carbon (OC) in watersheds CW1 and RW3, with regression equations fit to the data. The greater amount of OC in RW3 caused a significant difference in intercept values.

Table 4. Correlation coefficients between terrain attributes and soil properties (ρ_b and organic C [OC]) in two watersheds. Only coefficients with $P < 0.05$ are reported.

		Terrain attribute†				
Watershed	Soil property	Z	S	Log (A_{sc})	C_s	ω
		Correlation coefficient				
CW1	ρ_b‡	ns§	ns	ns	ns	ns
	OC	ns	−0.50***	ns	ns	ns
RW3	ρ_b	ns	ns	ns	0.30*	ns
	OC	ns	−0.45***	0.26*	−0.37**	0.36**

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† ω, topographic wetness index; A_{sc}, specific contributing area; C_s, surface curvature; S, slope; Z, relative elevation.
‡ ρ_b values determined by averaging across sample dates.
§ ns, not significant at $P > 0.05$.

Soil Moisture

Four dates of sampling in both watersheds provided a reasonable range of moisture conditions, given the logistics of having one individual conduct the sampling. Differences in θ were detected between watersheds and landscape positions by factorial ANOVA (Table 5). When θ was pooled among watersheds, toeslope and footslope positions had greater θ than at least one of the higher positions on three of the four dates. But when separated by watershed, differences in θ between landscape positions were significant in RW3 on two dates (28 Mar. 2003 and 15 May 2003) and were not detected in CW1 on any date. This possible discrepancy in spatial pattern did not lead to a significant (watershed by landscape position) interaction, although the P value for this interaction was 0.11 for θ values determined 15 May 2003.

There was greater antecedent precipitation on 15 May 2003 than the other dates (Table 2), and therefore this date also had the greatest θ values (Table 5). There were

Table 5. Statistical comparisons of water contents (θ) measured on four dates among and between landscape positions and watersheds.†

Sampling date	Landscape position	Soil water content: Mean (CW1 and RW3)	CW1 mean	RW3 mean	P (CW1 = RW3)‡
		% volume			
21 June 2002§	Ridge	23.4 b	23.4 a	23.4 a	ns
	Shoulder	24.2 ab	24.7 a	23.8 a	ns
	Backslope	24.4 ab	24.9 a	23.9 a	ns
	Footslope	25.1 a	25.2 a	25.0 a	ns
	Toeslope	24.8 a	24.3 a	25.2 a	ns
	All	24.4	24.6	24.3	ns
1 Nov. 2002	Ridge	33.8 a	33.1 a	34.1 a	ns
	Shoulder	33.9 a	33.5 a	34.2 a	ns
	Backslope	33.4 a	32.8 a	33.9 a	ns
	Footslope	34.3 a	33.3 a	35.2 a	0.04
	Toeslope	34.6 a	34.0 a	35.2 a	ns
	All	34.0	33.3	34.5	0.002
28 Mar. 2003	Ridge	30.9 c	31.7 a	30.3 c	ns
	Shoulder	31.6 bc	31.7 a	31.5 bc	ns
	Backslope	31.0 c	30.6 a	31.3 bc	ns
	Footslope	32.8 ab	32.6 a	33.0 ab	ns
	Toeslope	33.3 a	32.3 a	34.3 a	0.01
	All	31.9	31.7	32.0	ns
15 May 2003	Ridge	33.6 b	33.3 a	33.8 b	ns
	Shoulder	33.8 b	33.5 a	34.0 b	ns
	Backslope	33.6 b	33.1 a	34.1 b	ns
	Footslope	34.8 a	33.6 a	35.7 a	0.003
	Toeslope	35.4 a	34.0 a	36.5 a	0.002
	All	34.2	33.5	34.8	<0.001

† Comparisons between landscape positions (column-wise) are given by lettered significance groupings from Duncan's multiple range tests for each date; positions not sharing a letter are different at $P < 0.05$. In the last column, differences between watersheds (row-wise) are based on single-factor ANOVAs at each landscape position, and multiple-factor ANOVA (type III sums of squares) among positions.
‡ ns, not significant ($P > 0.05$).
§ For this date, an inverse transformation (X^{-1}) was applied to meet normality test.

significant differences in θ between watersheds at footslope and toeslope positions on 15 May 2003, but not at more than one landscape position on any other date (Table 5). RW3 had greater water contents than CW1 on the two dates with the wettest soil conditions, 1 Nov. 2002 and 15 May 2003. In fact, the *F* value from the factorial ANOVA (based on type III sums of squares) increased with mean θ (Fig. 4). This pattern would be expected given differences in soil properties between the watersheds, as will be shown later. Differences in antecedent precipitation on 15 May 2003 (Table 2) could only have muted this pattern. We expect the greater antecedent precipitation in CW1 should have redistributed below the 0.2-m sampling depth before sampling on 15 May. If this did not occur, however, then the observed difference in θ (Table 5) would have been greater had antecedent rainfall amounts been equivalent.

Localized variation in θ had only a small influence on our results. In both watersheds, there were replicate samples taken at each row position in November 2003, and replicate samples, bulked among row positions, taken in May 2003. Variance in θ among these replicates was ≤3% of the total sample variation in each case.

Significant correlations between terrain attributes and θ (Table 6) occurred more frequently in RW3, which was consistent with ANOVA results for landscape positions (Table 5). Curvature was the terrain attribute most

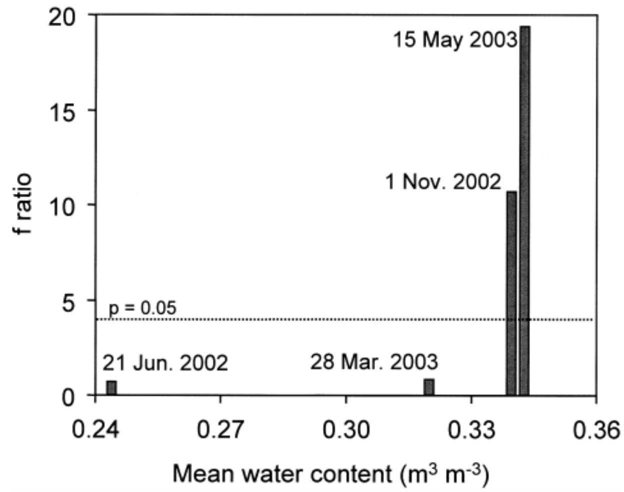

Fig. 4. Plot of average surface-soil θ measured on four dates in CW1 and RW3 versus the *F* ratio, which indicates the significance of the difference between watersheds after landscape-position effects were removed. RW3 had significantly larger θ on dates when θ exceeded 33%.

consistently correlated with θ across the four dates and two watersheds. Kachanoski and de Jong (1988) also highlighted the influence of curvature on soil moisture distributions. In RW3, all five terrain attributes had significant correlations with θ on the two dates that ANOVA detected significant differences between landscape positions (28 Mar. and 15 May 2003). However, in CW1, C_s and A_{sc} were the only terrain attributes correlated with θ on more than one date.

Wetness index (ω) did not have the strongest correlations with soil moisture, partly because these silt-loam

Table 6. Correlation coefficients significant at $P < 0.05$, between surface soil water contents on four dates and terrain attributes in two watersheds.†

Watershed	Sampling date	Terrain attribute‡: Z	S	Log (A_{sc})	C_s	ω
		Correlation coefficient				
CW1	21 June 2002	ns§	ns	0.32*	−0.31*	ns
	1 Nov. 2002	ns	ns	0.30*	−0.39**	ns
	28 Mar. 2003	ns	ns	0.35*	−0.46***	0.31*
	15 May 2003	ns	ns	ns	−0.40**	ns
RW3	21 June 2002	−0.43***	ns	ns	ns	ns
	1 Nov. 2002	ns	−0.41**	ns	−0.32*	0.28*
	28 Mar. 2003	−0.38**	−0.28*	0.45***	−0.56***	0.48***
	15 May 2003	−0.35**	−0.42***	0.38**	−0.39**	0.44***

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† Note a difference in sample sizes between watersheds alters the *P* value of a given correlation coefficient. For example, in CW1 ($n = 50$), $r > 0.27$ is significant at $P = 0.05$. Whereas, in RW3 ($n = 62$), an *r* of 0.25 is significant at this level.
‡ Z, relative elevation; S, slope; A_{sc}, specific contributing area; C_s, surface curvature; ω, topographic wetness index.
§ ns, not significant at $P > 0.05$.

Table 7. Correlation coefficients between soil constituents and θ as measured on four dates in two watersheds.†

Watershed	Date θ measured	Soil property (% mass) OC‡	Silt	Clay	Stepwise regression result equation	r^2
		Correlation coefficient				
CW1	21 June 2002	ns§	−0.34*	ns	0.40 − 0.003 (silt)	0.10
	1 Nov. 2002	ns	ns	ns	ns	–
	28 Mar. 2003	ns	ns	ns	ns	–
	15 May 2003	ns	−0.32*	0.41**	0.22 + 0.003 (clay)	0.17
RW3	21 June 2002	0.37**	ns	ns	0.19 + 0.02 (OC)	0.13
	1 Nov. 2002	0.63***	0.32*	−0.33**	0.18 + 0.04 (OC) + 0.004 (silt)	0.52
	28 Mar. 2003	0.54***	ns	ns	0.23 + 0.04 (OC)	0.32
	15 May 2003	0.33**	ns	ns	0.31 + 0.02 (OC)	0.11

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† Note a difference in sample sizes between watersheds ($n = 50$ in CW1, 62 in RW3) alters the P value of a given correlation coefficient.
‡ OC, organic C.
§ ns, not significant at $P > 0.05$.

soils are deep, uniform, and well drained. The successful prediction of θ by ω is based on the assumed importance of lateral flows at a shallow soil depth, which occur where hydraulic conductivity decreases with depth (Wilson and Gallant, 2000). But these deep loess soils are uniform; vertical water movement is not restricted, and shallow, lateral flow should be infrequent.

The capacity of terrain attributes to predict θ was limited in both watersheds, but slightly better in RW3. The strongest correlations in both watersheds were obtained for 28 Mar. 2003 data (Table 6), when variability in θ was also greatest. Across the four dates, simple linear regression equations accounted for 10 to 21% of the variation in θ in CW1, and 17 to 30% in RW3, with C_s most frequently being the best single predictor of θ. Second order relationships with interaction terms could only improve the r^2 to about 0.40 (regression results not shown). Summarizing results for θ, RW3 had larger mean θ under the wettest soil conditions we compared (Table 5, Fig. 4). Spatial patterns of θ were more distinct in RW3, as indicated by significant differences in θ between landscape positions in RW3 on two dates, and greater correlations between terrain attributes and θ in RW3.

Influence of Soil Properties on Soil Water Content

Significant correlations between soil properties and θ occurred, but differed between the two watersheds (Table 7). In particular, significant OC–θ correlations occurred on all four dates in RW3, but on none of the dates in CW1. The larger concentration of OC in RW3 had a consistent influence on θ in that watershed (Fig. 5); note that variations in OC are similar, with standard deviations of 0.30% in CW1 and 0.33% in RW3. There were weak, but significant correlations between textural separates and θ on two dates in CW1, but only on one date in RW3. Regression results (Table 7) confirmed soil properties had a more consistent influence on spatial patterns of θ in RW3 than in CW1.

The observed differences in water contents between watersheds (Fig. 4) are consistent with smaller ρ_b and greater aggregate stability (Cambardella et al., 2004) in RW3, which would lead us to expect greater porosity and water-holding capacity for the conservation watershed. Application of pedotransfer functions (adapted from Mayr and Jarvis, 1999) to our soils data supports this statement. In particular, with the observed differences in ρ_b, OC, and texture, pedotransfer function results would lead us to expect the greatest (and most easily detectable) differences in θ between watersheds when soils are wet (Fig. 6). The expected differences are close to those we observed (Table 5). Plotting mean θ values for each watershed on the soil water characteristic curves obtained from the pedotransfer functions (Fig. 6) provides evidence that average ψ values were similar in the two watersheds on the sample dates. The four sampling dates covered about half the variation in θ expected for ψ ranging between −100 and −15 000 cm (Fig. 6). The hydraulic

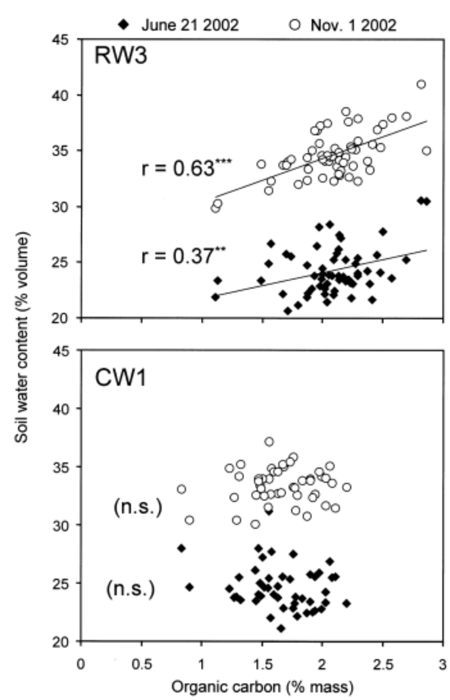

Fig. 5. Plots of organic C (OC) and soil water contents on two dates in watersheds CW1 and RW3. Correlation coefficients were consistently significant in RW3 ($P < 0.01$), and consistently nonsignificant in CW1 ($P > 0.05$).

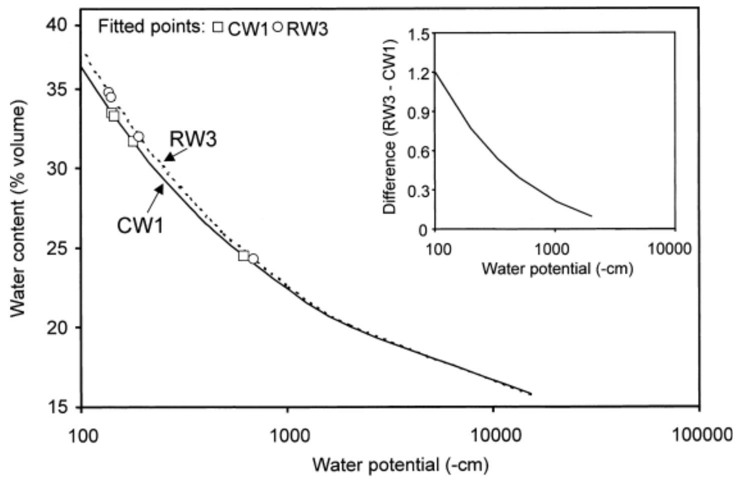

Fig. 6. Soil water retention curves for the conventionally tilled (CW1) and ridge-tilled (RW3) watersheds, as estimated by pedotransfer functions. Watershed means for θ_s and b (Eq. [1], Table 8) were used to plot these curves. Plotted points place the mean θ values for four dates of monitoring in both watersheds, indicating soil water potentials were similar between watersheds. Inset: predicted differences in θ between watersheds are greatest when soils are wet, and similar to those detected (Table 5).

parameters θ_s and b (Eq. [1]), used to obtain water retention curves (Fig. 6) were significantly different between watersheds at every landscape position (Table 8). Also, differences in hydraulic parameters between landscape positions were only significant in RW3. Therefore, variation in soil properties between watersheds and landscape positions (Tables 1 and 3) create variations in water-holding characteristics between watersheds and landscape positions (Table 8) that are consistent with our observations of θ (Table 5, Fig. 6).

Temporal Stability

Correlation coefficients among θ values from different dates, indicating the temporal stability of spatial patterns in θ, were not consistent between CW1 and RW3 (Table 9). In CW1, the three dates with large mean θ (>30% volume) showed strong intercorrelations ($0.66 < r < 0.80$), but the driest date (21 June 2002) had small correlations with the dates having $\theta > 30\%$ ($r < 0.39$). In RW3, correlations among the four dates were all significant ($P < 0.05$) but weak ($0.26 < r < 0.54$). In CW1, stable spatial patterns were apparent during wet conditions simply because several steep and/or convex locations at shoulder or backslope positions persistently had the smallest θ values (data not shown). Therefore, stability of θ spatial patterns in these watersheds was at best weak, compared to other studies where correlation coefficients for θ collected on different dates exceeded 0.8 (da Silva et al., 2001; Tomer and Anderson, 1995). Differences in seasonal conditions on our sampling dates (Table 2) may explain why. Among the four dates of sampling in both watersheds, the variation of θ was greatest on 28 Mar. 2003 (standard deviations of 2.3% in CW1 and 2.6% in RW3), and least on 15 May 2003 (standard deviations of 1.4% in CW1 and 1.9% in RW3) when mean θ was greatest. Small variation in θ under wet conditions (observed 1 Nov. 2002 and 15 May 2003) may reflect uniform infiltration of recent precipitation, whereas large variation observed at the end of winter (28 Mar. 2003) could result from redistributions of runoff, snowmelt, and perhaps, in partially thawed soils, shallow soil water. This could explain why spatial patterns of θ were best accounted by terrain characteristics (particularly ω) at the end of winter, and not

Table 8. Hydraulic parameters for Eq. [1] estimated using pedotransfer functions of Mayr and Jarvis (1999).†

Parameter	Landscape position	CW1 and RW3 (pooled)	CW1	RW3	P (CW1 = RW3)
		% Volume			
θ_s	Ridge	54.4 a	53.0 a	55.0 a	0.006
	Shoulder	54.2 a	52.9 a	55.4 a	<0.0001
	Backslope	54.4 a	52.9 a	55.7 a	<0.0001
	Footslope	54.3 a	52.5 a	55.5 a	0.0002
	Toeslope	54.4 a	52.7 a	55.7 a	<0.0001
	All	54.3	52.8	55.5	<0.0001
		No units			
b	Ridge	2.61 a	2.73 a	2.55 b	0.024
	Shoulder	2.64 a	2.71 a	2.57 ab	0.010
	Backslope	2.66 a	2.69 a	2.64 a	0.008
	Footslope	2.66 a	2.76 a	2.59 ab	<0.0001
	Toeslope	2.65 a	2.68 a	2.61 ab	0.006
	All	2.65	2.71	2.60	<0.0001

† Comparisons between landscape positions (column-wise) are given by lettered significance groupings from Duncan's multiple range tests; positions not sharing a letter are different at $P < 0.05$. Differences between watersheds (row-wise), in the last column, are based on single-factor ANOVAs at each landscape position, and multiple-factor ANOVA (type III sums of squares) among positions.

Table 9. Correlation coefficients between θ values determined on four different dates in two watersheds.

	CW1				RW3			
Date θ measured	21 June 2002	1 Nov. 2002	28 Mar. 2003	15 May 2003	21 June 2002	1 Nov. 2002	28 Mar. 2003	15 May 2003
	Correlation coefficient							
21 June 2002	1				1			
1 Nov. 2002	0.39**	1			0.26*	1		
28 Mar. 2003	0.29*	0.66***	1		0.43***	0.45***	1	
15 May 2003	ns†	0.78***	0.80***	1	0.36**	0.33*	0.54***	1

* $P < 0.05$.
** $P < 0.01$.
*** $P < 0.001$.
† ns, not significant at $P > 0.05$.

necessarily when θ was greatest. Therefore, we have some evidence that spatial patterns of θ in these watersheds shift seasonally, a phenomenon well explained elsewhere (Western et al., 1999).

CONCLUSIONS

Differences in ρ_b and OC were found between watersheds. Such differences were identified in 1995 and remained detectable in 2003, 8 yr after the conventionally tilled watershed was converted to no-till. Mean differences between watersheds were about 0.1 Mg m^{-3} in ρ_b and about 0.4% in OC. Spatial patterns of OC occurred in both watersheds, with the least OC at backslope positions in both watersheds. Accordingly, slope (S) was the single terrain characteristic that best predicted OC (r^2 of 0.21–0.25). There was no clear evidence that spatial patterns of OC in the two watersheds were different. Small but significant differences in texture occurred between watersheds and among landscape positions.

Surface-soil θ showed differences between landscape positions and watersheds, with significantly greater water contents found in the ridge-tilled watershed on two sampling dates when $\theta > 0.33$ m^3 m^{-3}. Surface curvature (C_s) was the terrain attribute most commonly correlated with θ. Spatial patterns in θ were more distinct in the ridge-tilled watershed, because differences between landscape positions were found in that watershed but not the conventionally tilled watershed, and terrain characteristics had greater capacity to predict θ in the ridge-tilled watershed.

Soil OC showed greater correlation with θ in the ridge-tilled watershed than in the conventionally tilled watershed. When we applied pedotransfer functions to our soils data, we found differences in soil water retention characteristics between landscape positions, but only in the ridge-tilled watershed. Also, soil-water retention curves, obtained from the pedotransfer functions, showed differences in θ between watersheds should be greatest (and most detectable) under low soil-water potentials, corroborating results under Objective 2. Differences in soil texture, ρ_b and OC between watersheds all contributed to consistent differences in θ that were measured in the field and predicted by pedotransfer functions. We infer that in the conventionally tilled watershed, long-term effects of conventional tillage may have obscured spatial patterns of soil properties that influence soil-water retention.

Intercorrelations between θ on different sampling dates were significant, but smaller than reported in other studies. Therefore temporal stability of θ was limited. Seasonal differences in spatial patterns of θ may result from varying infiltration, runoff, or lateral movement of water through mechanisms that may be important during winter.

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